AXIAL INJECTION BEAM-LINE OF C400 CYCLOTRON FOR HADRON THERAPY: PARTICLES DYNAMICS AND MAGNETIC FIELD SCREENING

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Abstract

The axial injection beam-line of the C400 cyclotron for hadron therapy is presented. The influence of the strong magnetic field from the cyclotron on particles dynamics is taking into account during simulation. The effect of the beam space charge neutralization due to residual gas in the beam-line on parameters of the injected beam is evaluated. The screening of the optical elements and an influence of the injection channel shielding elements on magnetic field of the C400 cyclotron is studied. The 3D ANSYS model is used for this purpose.

INTRODUCTION

The axial injection system is the part of cyclotron C400 for Hadron therapy developing by IBA (Louvain-la-Neuve, Belgium) [1] in collaboration with JINR (Dubna, Russia). This cyclotron will be used for therapy of cancer using either protons or light ions. $^{12}C^{6+}$ and $^{4}He^{2+}$ ions will be accelerated to energy 400 MeV/amu and extracted by the electrostatic deflector, H_2^+ ions will be accelerated to the energy 260MeV and extracted by stripping. System of injection allows the transportation of ion beams from ion sources to median plane of cyclotron with 100% efficiency.

STRUCTURE OF INJECTION CHANNEL

General layout of the axial injection system is shown in Fig.1.

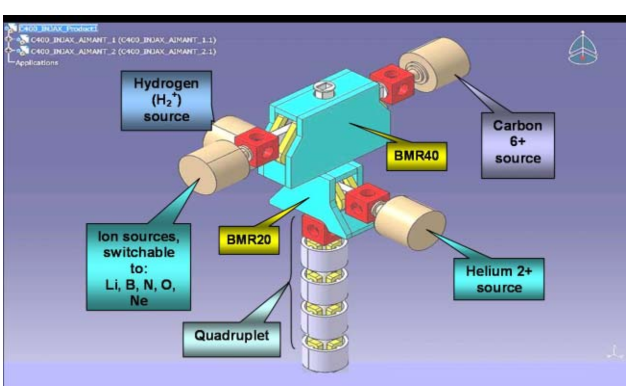

Figure 1: View of axial injection channel

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The ion source injects directly into the switching magnet, which is also used as a charge state analyzing magnet. The ion source exit electrode is located at 40 cm from the entrance of the magnet (effective field boundary). Between the source insulator and the magnet entrance we provide a cube to connect a vacuum pump and install a removable beam stop to measure the total current extracted from the ion source. The input face angle of the 90° magnet is selected to focus the beam into the analyzing slits which are located in a cube placed just after the second magnet. The first magnet (BMR40), to be used for the Carbon ECR source (and perhaps for an optional ion source for Lithium) has a bending radius of 40 cm. The second magnet (BMR20), to be used for the alpha and for the $^2H^{1+}$ ion source does not need a very high resolution, and has a bending radius of 20 cm.

At the exit of the second magnet diagnostic box is placed which will include two pairs of remotely adjusted slits, an insertable beam stop (faraday cup), and a vacuum pump. The quadruplet of quadrupoles adapts the optics to get beam matched with acceptance of the spiral inflector of the cyclotron.

The length of the vertical part of injection channel is about 5 m from the carbon ECR axis to the median plane of the cyclotron C400.

The time to change species can be not more than two minutes to retune the beam transport line between different treatment rooms.

MAGNETIC FIELD IN CHANNEL

The main particularity in design study of the axial injection system is presence of a strong magnetic field in vertical part of channel (see Fig.2, red line) and significant one (500 – 1000 G) in the bending magnets region. Big value of this field affects significantly the particles trajectories and leads to necessity of shielding the horizontal parts of the injection channel as well as the bending magnets. As it was shown in [2] this value must be less than 10 – 15 G to avoid the significant particle losses.

The possibility of cyclotron magnetic field suppression was studied with the help of 2D and 3D model [3]. The distribution of the longitudinal magnetic field in the presence of the screen calculated by using POISSON code [4] is shown in Fig.2 (black line). In the region of quadruplet the magnetic induction reaches 5000 Gauss.

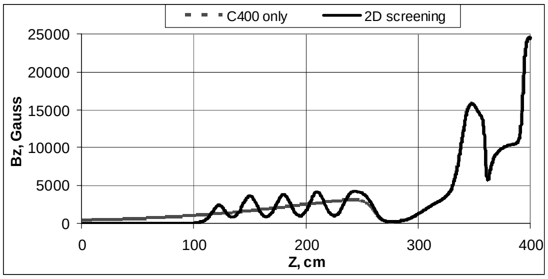

Figure 2: C400 cyclotron magnetic field distribution

3D simulation by ANSYS code was fulfiled using the following model of shielding (Fig.3).

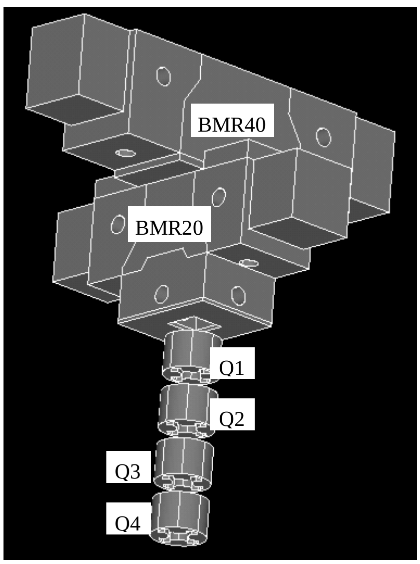

Figure 3: Overall view of screened injection channel.

The thickness of lateral walls of bending magnets is increased from 5 cm up to 15 cm. The clearance between the magnets is filled by a steel insertion. A hole inside this insertion is a rectangle with sides of 25 and 20 cm. An insertion down stream BMR20 shields a part of vertical channel with length 27 cm. A hole of this element is a square with a side of 20 cm. Additional insertions are used for shielding of horizontal channels from ECR ion sources to bending magnets BMR40 and BMR20. These insertions have rectangular holes with the dimensions 33 × 20 cm and 24 × 20 cm correspondingly. Top walls of insertions shielding horizontal beam lines to bottom magnet BMR20 have a thickness of 15 cm. All insertions provide holes as well as diagnostic boxes. Shielding insertions around ECR ion sources are also used in ANSYS model. The mass of the shielding elements excluding the original magnets is about 5.4 tons.

Proposed shielding permits to reduce the C400 magnetic field just in whole the region of bending magnets and horizontal channels up to value less than 10 G except the edges of bends where the field can reach of about 20 G. The screening of the injection channel results in increasing the level of magnetic fields of the bends on 10 – 20 G. Such small change of the level (≤ 2%) inside the bending magnets can be compensated by reduction of current in coils.

INFLUENCE OF SHIELDING ON MAGNETIC FIELD IN MP OF C400

2D and 3D simulations have shown that the screening elements influence on the magnetic field in the C400 median plane. Negative radial component of the magnetic field appears and its average absolute value increases with radii up to 10 – 12 G. Moreover the radial component in the valleys has greater absolute values than between sectors. Azimuthal component of the field is less significantly and does not exceed 1 G just in whole MP. Axial component increases on about 15 G. In contrast to the radial component it possesses greater values between sectors of the cyclotron.

INITIAL BEAM DATA

The main parameters of ion beams used in calculations contains in Table 1.

Table 1: Main beam parameters

Ion energy, keV / Z	25
“Carbon” beam current, eμA	1202
^{12}**C**$^{6+}$ ion beam current, eμA	1
Emittance, π mm·mrad	30
Beam radius, cm	0.5
He^{1+} ion beam current, eμA	200
^{4}**He**$^{2+}$ ion beam current, eμA	20
Emittance, π mm·mrad	50
Beam radius, cm	0.3
^{2}**H**$^{1+}$ ion beam current, eμA	20
Emittance, π mm·mrad	60
Beam radius, cm	0.3

BEAM DYNAMICS SIMULATION

Simulation of beam dynamics in injection channel was fulfilled using the last version of the Multi Component Ion Beam code (MCIB04 [5]).

Fitting of lenses gradients was produced within the framework of the moment method. The initial conditions for the moments of ion beams were defined at the exit of BMR20 and were found by macro-particle simulation. Charge state distributions for each ion source (Fig.4) and beam self-fields were taken into account.

The matching condition at the entrance of the spiral inflector correspond to the steady state of the beam (beam without envelopes oscillation) in the uniform magnetic field with magnitude to be equal to the field in the cyclotron center. For minimization of functional the simplex method was used.

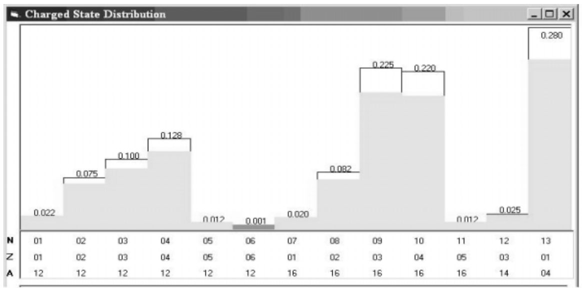

Figure 4: Carbon beam charged state distribution:
N – ordinal number; Z – ion charge, A – ion mass

All results were checked by macro-particle method. For all ion species the results of the macro-particle and moment method simulation ones are in a rather good agreement.

Particle trajectories, ion distributions in phase planes at entrance of spiral inflector for carbon $^{12}C^{6+}$ are shown in Fig.5, 6 respectively.

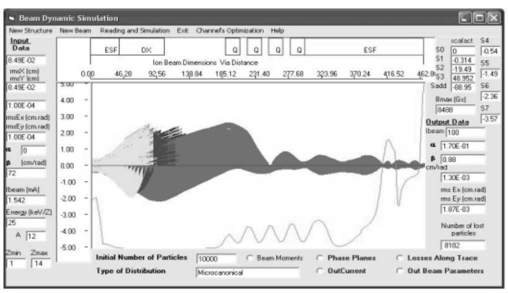

Figure 5: Results of macro particle simulation for $^{12}C^{6+}$. Green line shows distribution of magnetic field

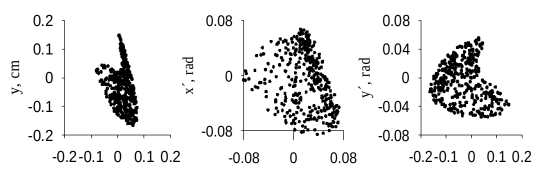

Figure 6: $^{12}C^{6+}$ ions distributions in phase planes at entrance of spiral inflector

Analogous results were obtained for another two ion species. The matching conditions of the optical functions with the acceptance of the cyclotron inflector were satisfied in all cases.

Table 2: Parameters of quadrupole lenses

	Tilt, rad	Quadrupole coefficient K1, m^{-2}			Quadrupole gradient G/cm		
		$^{12}C^{6+}$	$^{4}He^{2+}$	$^{2}H^{1+}$	$^{12}C^{6+}$	$^{4}He^{2+}$	$^{2}H^{1+}$
Q1	**0.55**	**-0.337**	**11.048**	**10.33**	**-1.09**	**35.57**	**33.26**
Q2	**1.50**	**-19.51**	**1.534**	**6.99**	**42.79**	**4.94**	**22.52**
Q3	**2.37**	**49.12**	**21.93**	**11.28**	**158.14**	**70.59**	**36.22**
Q4	**3.57**	**-88.33**	**62.13**	**81.51**	**-284.4**	**200.01**	**262.4**

For reducing of the coupling in the longitudinal magnetic field (and as effect the emittance growth) the quadrupoles have to be turned around the longitudinal axes by required angles (tilted lenses) [6]. The quadrupole coefficients of the lenses and the tilt angles for all ion species are contained in the Table 2.The maximal value of gradients do not exceed 300 G and tilt angles are independent on the ion sort. As result the beam envelopes inside the spiral inflector are equal to 1 mm (Fig.7).

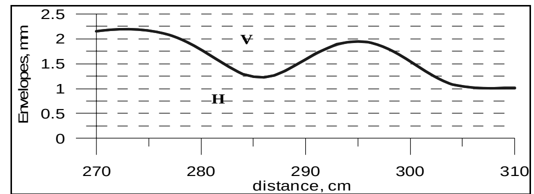

Figure 7: $^{12}C^{6+}$ beam envelopes near inflector

BEAM NEUTRALIZATION

The simulation show that neutralization of the hydrogen and helium beams up to high degree (f_N =1) does not have essential influence on beam dimensions and divergences and may be compensate by insignificant changes of the quadrupoles gradients.

In the case of carbon ions (big value of the initial beam current) quadrupole gradients have to be optimized for each neutralization factor. Moreover the displacement of beam center of mass is the function of neutralization factor too. The reason of this displacement is common electrostatic action of ions of different species on the beam center of $^{12}C^{6+}$ ions during separation. So the strength of magnetic field in vertical dipole BMR40 must be optimized to minimize this displacement [6].

REFERENCES

[1] G. Karamysheva et al, IBA C400 cyclotron project for hadron therapy. These proceedings MOYCR01.

[2] V.S.Alexandrov, G.G.Gulbekian, N.Yu. Kazarinov, V.F.Shevtsov, A.V.Tikhomirov. Numerical simulation of the $^{48}Ca^{5+}$ ions transport along the U-400 cyclotron's injection line. In: Proc of the 16-th Int. Conf. on Cyclotron and their Applications, May 13-17, 2001, East Lansing, Michigan, USA, p. 390.

[3] N. Kazarinov et al. Screening of cyclotron magnetic field in C400 axial injection beam-line. In: Proceedings of the PAC07, 25-29 June, 2007, Albuquerque, USA, p.1559.

[4] POISSON Program, Los Alamos Acc.Group, LA-UR-87-115, 1987.

[5] V. Aleksandrov, N. Kazarinov, V. Shevtsov, Multi-Component Ion Beam code - MCIB04, Proc. XIX Russian Particle Accelerator Conference (RuPAC-2004), Dubna, Russia, 2004, p.201.

[6] N.Yu.Kazarinov at al, Axial Injection Beam-Line of C400 Cyclotron for Hadron Therapy. In: Proceedings of the PAC07, 25-29 June, 2007, Albuquerque, USA, p.1562.